

GEOPHYSICAL VOID DETECTION DEMONSTRATIONS

Kanaan Hanna, Bart Hoekstra, Jim Pfeiffer and Brandy Uphouse

ZAPATAENGINEERING, Blackhawk Division

ABSTRACT

This paper describes the results of geophysical field demonstrations conducted at a known abandoned underground coal mine, eastern Illinois. This investigational program, in cooperation with the US Department of Labor Mine Safety and Health Administration (MSHA), was designed to advance current state-of-practices of geophysical technologies for detecting underground mine voids. Old mine works present major health and safety hazards to miners who have inadvertently cut into locations with such features. In addition, the presence of abandoned mines beneath roadways has a great impact on the performance of the transportation infrastructure in terms of cost and public safety. Both are of major concern to the States Department of Transportation (DOT). Roads constructed over abandoned mines are subject to potential differential settlement, subsidence, sinkholes, and/or catastrophic collapse. Thus, there is a need to utilize geophysical imaging technologies to map and locate old mine works.

Several surface and borehole geophysical imaging methods and mapping techniques were employed at the investigation site to delineate the location and extent of old works. These included: 1) surface high-resolution seismic (HRS) using compressional P-wave (HRPW) and shear S-wave (HRSW) reflection methods collected with three-dimensional (3-D) techniques; 2) crosshole seismic tomography; 3) guided waves; 4) reverse vertical seismic profiling (RVSP); and 5) borehole sonar mapping.

In order to confirm the presence of old mine workings, several confirmation boreholes were drilled which confirmed the presence of the imaged mine voids. Based on the results and analysis obtained from the geophysical and void drilling confirmation investigations, ranking factors were developed to evaluate the performance of the geophysical technologies deployed at the test site. The evaluation has shown the effectiveness of the RVSP as the most viable method to both accurately and economically detect the old mine works and locate confirmation boreholes. The RVSP method can be complemented by the use of borehole mapping tools such as sonar (for water-filled voids) or laser (for air-filled voids) to determine the vertical and lateral extent of the voids. This paper presents the results obtained from the HRPW and HRSW surface seismic surveys along with the RVSP and sonar mapping.

The information obtained from the RVSP and sonar mapping can then be used by: a) the mine operator to perform exploratory drilling while approaching detected old mine works to avoid cutting into the voids thus eliminating unexpected hazardous conditions; and b) State DOT engineers involved in geotechnical site investigations, road rehabilitation and construction, and risk assessment of the potential of roadway collapse and remediation efforts.

SITE DESCRIPTION

The known abandoned mine test site was located adjacent to an active room-and-pillar coal mine in the east-central subdivision of the Illinois coalfield, near Georgetown, Illinois. The primary geologic feature of interest within the active underground mine is the Herrin #6 (Herrin) coal seam. This seam is one of the most important strata of coal located near the top of the Pennsylvanian-Period Carbondale Formation and averaged six feet thick at a depth of approximately 235 ft. The abandoned mine operated from 1917 to 1947 and used room-and-pillar methods to mine the Herrin #6 coal seam. Based on the available historical mine maps, the mine layout consisted of four-entry mains oriented north-south which branched into two-entry submains oriented east-west and production rooms. The entries are 10 ft wide separated by pillars that are 20 ft wide and 40 to 60 ft long.

The test site was located on private agriculture property. The property consisted of an open field partially cultivated and intersected by a tree line, wire fence, power lines, and a dirt access road. Figure 1 is representative of site conditions showing the plowed portion of the test area during data collection.



Figure 1. HRS Source and Receiver Locations.

GEOPHYSICAL METHODS

The selected geophysical methods were employed at the same survey site to provide: 1) a more comprehensive data interpretation; 2) the basis for the performance evaluation; and 3) to determine the advantages and limitations of these technologies to detect accurately mine voids in a cost-effective manner. This paper focuses on the results obtained from the 3-D HRS (HRPW and HRSW), RVSP, and sonar mapping surveys.

The HRS survey grid, whose size is 150 by 1050 ft, was strategically positioned so that the grid would overlay both the mined and un-mined coal areas. This layout allowed the survey to cross diagonally over two portions of the old mine entry system; i.e., the four-entry mains in the north-south direction and the two-entry submains in the east-west direction. Figure 2 shows the location of the HRPW and HRSW 3-D reflection survey grid. The data were acquired using a vibratory seismic source (one vibrator during P-wave data acquisition and two synchronized vibrators during S-wave data acquisition), a 144-channel seismograph, and high frequency geophones (see Figures 3 and 4).

RVSP is a special type of seismic reflection survey that deploys a source in a borehole in conjunction with surface geophone arrays, which are used to record the reflected seismic signals.

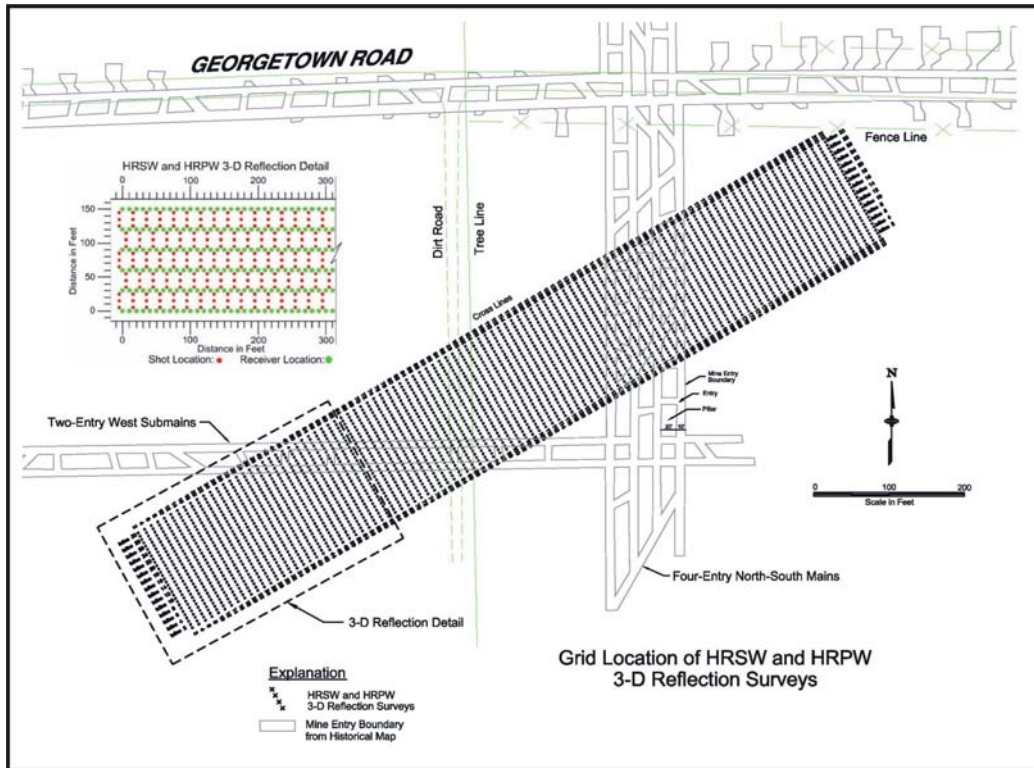


Figure 3. Grid Locations of HRSW and HRPW 3-D Reflection Survey.



Figure 3. HRS Acquisition using Dual MicroVib Source.



Figure 2. HRS Recording System.

The data used for the RVSP processing were obtained from a subset of the data collected from a cross-hole tomography survey that was also conducted as part of this demonstration. The survey geometry was not optimal for the RVSP acquisition; however, these data were of sufficient

quality to provide better images of the old mine works. A Bolt DHS 5500 air gun was deployed with a 2.5 cubic inch air chamber and the signals were recorded on single Mark Product 40 Hz geophones spaced at 10 ft intervals in a line between the boreholes used in the cross-hole tomography survey. The typical distance between boreholes was 200 ft. The source was activated 10 times per shotpoint at nominal 2 ft shotpoint intervals. Three 2-D RVSP data sets were collected in this manner.

The design and acquisition geometry for the RVSP (i.e., number of surface geophones and offset, depth of borehole, and source interval), will depend on the amount of information available on the old mine works including void/pillar geometries, target depth, geology, and resolution required. An optimal layout for an RVSP survey along a 2-D line is shown on Figure 5. The boreholes should be spaced at a distance approximately equal to twice the depth of the target and drilled to a depth above the target horizon. For shallow

targets, up to about 200 ft, the required depth of the source borehole may vary from five ft to 20 ft above the target horizon. For deeper targets; up to 1,000 ft, the borehole depth may vary from 50 ft to 200 ft above the target horizon depending on the target size being investigated. When multiple coal seams are present, the borehole should be drilled to a depth below the coal seam immediately above the target horizon. Similarly, the geophone spacing may vary from two ft to 10 ft for shallow and deep targets, respectively. The surface geophones could then be laid out in a line extending between the boreholes and the source deployed in each of the boreholes. This will allow continuous coverage over the entire length of the line between the boreholes. Additional boreholes could be located along a line, depending on the distance that is required for an investigation.

This method can be extended to a 3-D survey around the borehole, although this would require some increase in cost for additional equipment, field effort, and processing time. Therefore, 3-D surveys should only be performed when very little information is available on the location and orientation of the old mine works.

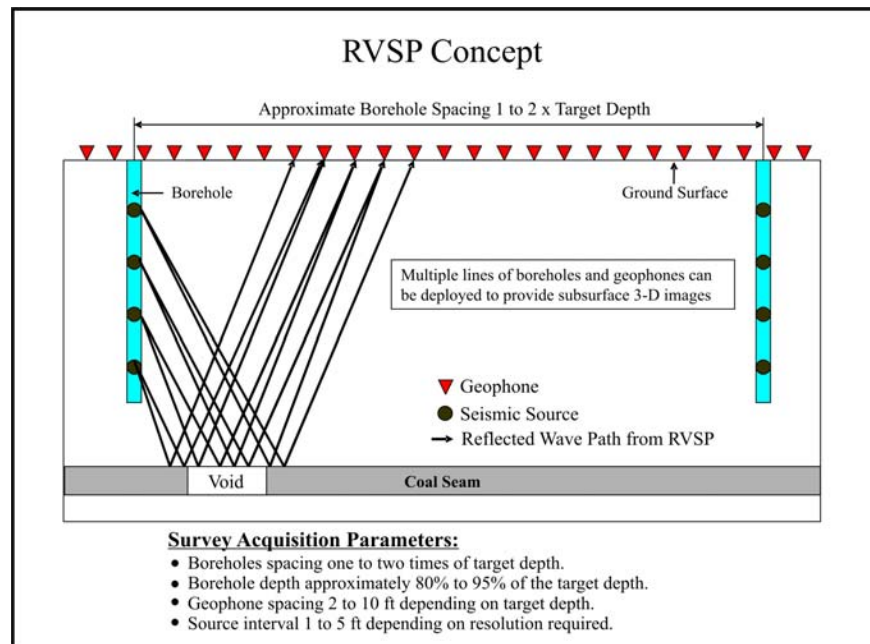


Figure 5. Schematic of Recommended RVSP Survey to Detect Old Mine Workings.

DISCUSSION OF RESULTS

The following summarizes the significant results obtained from the HRS (HRPW and HRSW), RVSP, and sonar mapping surveys.

HRPW and HRSW 3-D – The high-resolution primary wave method obtained clear reflection from the Herrin #6 coal seam, and showed consistent data quality throughout the survey (Figure 6). As shown on the figure, the north-south mains are well defined while the submains are somewhat less defined. Amplitude variations are clustered around the old mine works, in addition to extending out beyond the area of the historical mine works. These high amplitude anomalies may correspond to old mine works not shown on the historical mine map, thinning of coal seam, presence of rolls, and/or variations in the vertical and horizontal stresses. The high amplitude anomaly north of the submains was further investigated during void drilling confirmation. Boring in this area had confirmed a five ft thick solid coal seam, which might be indicative of the presence of rolls in the coal seam roof.

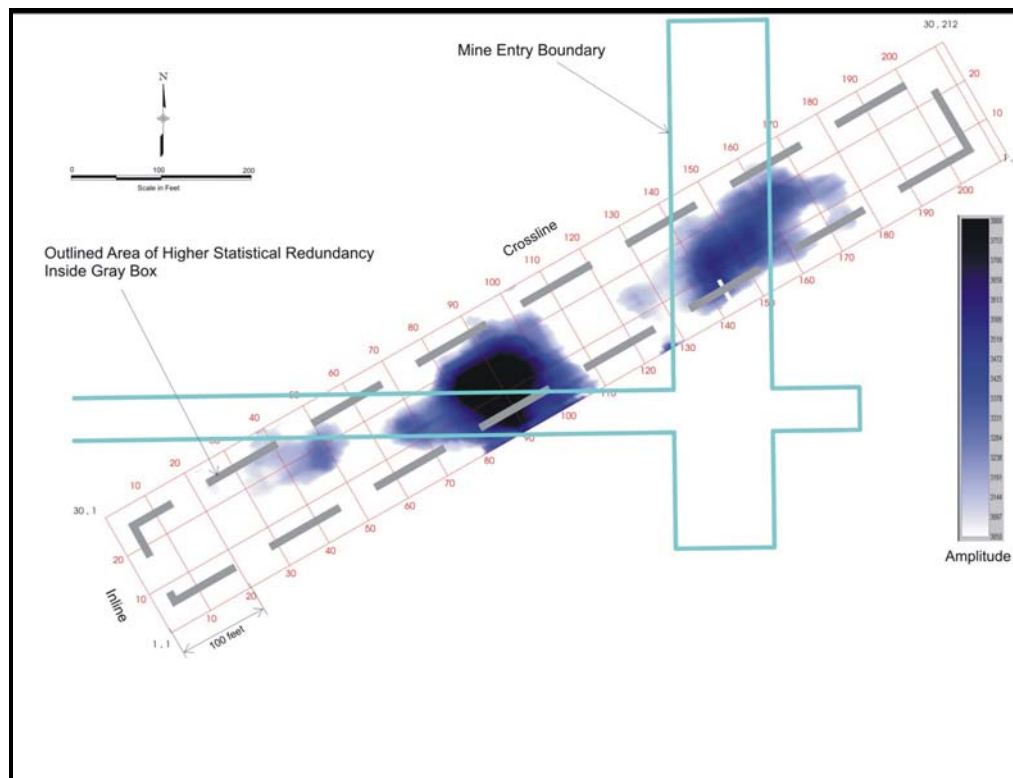


Figure 6. Anomalous Coal Response from P-Wave Analysis.

The S-wave method obtained some reflection data from the upper coal horizon (Danville #7 which is approximately 90 ft above Herrin #6), but little information was obtained from the Herrin #6 coal seam itself. This is due to the high reflection coefficient of the upper coal seam that limited the transmission of the S-wave seismic energy below it. Acquisition of shear wave data was also hindered by the soft soils in the near surface and partially plowed fields in this

area. Although two vibrators were deployed to increase the source energy output, the seismic energy was still insufficient to adequately compensate for the signal loss.

The P-wave, and to a lesser degree the S-wave data, did identify the general area of the old mine works, but neither of the methods identified the location of the individual rooms (voids) and/or pillars. The amplitude response seen in the P-wave and S-wave data is the result of the combined effect of the rooms and pillars.

The cost of conducting and processing the P-wave and S-wave 3-D surveys for this demonstration program was relatively high. Therefore, the P-wave method may be feasible to use in situations where the target is shallower and near-surface conditions provide better transmission of the seismic energy. Because the compressional-wave velocities of coal and water are very similar (4,900 ft/sec vs 5,200 ft/sec), improved results may also be obtained if the voids are air-filled. The S-wave survey was originally selected because of the high impedance contrast between coal and both air-filled voids and water-filled voids. S-waves have an advantage over P-waves for void detection because S-waves do not propagate through water or air, such that the void contents should not affect the ability of S-waves to detect a void. The S-wave method potentially could be used in areas where the uppermost coal seam is the target, where no overlying coal seam would prevent the transmission of the S-wave energy.

RVSP – The RVSP data were processed using a processing flow that included a proprietary imaging transform developed by Sterling Seismic Services. An example of one of the processed RVSP profiles is shown on Figure 7, for the section between boreholes NS #6 and NS #4. The solid line in the index map (Figure 7) represents the area with data coverage. The plot is displayed in

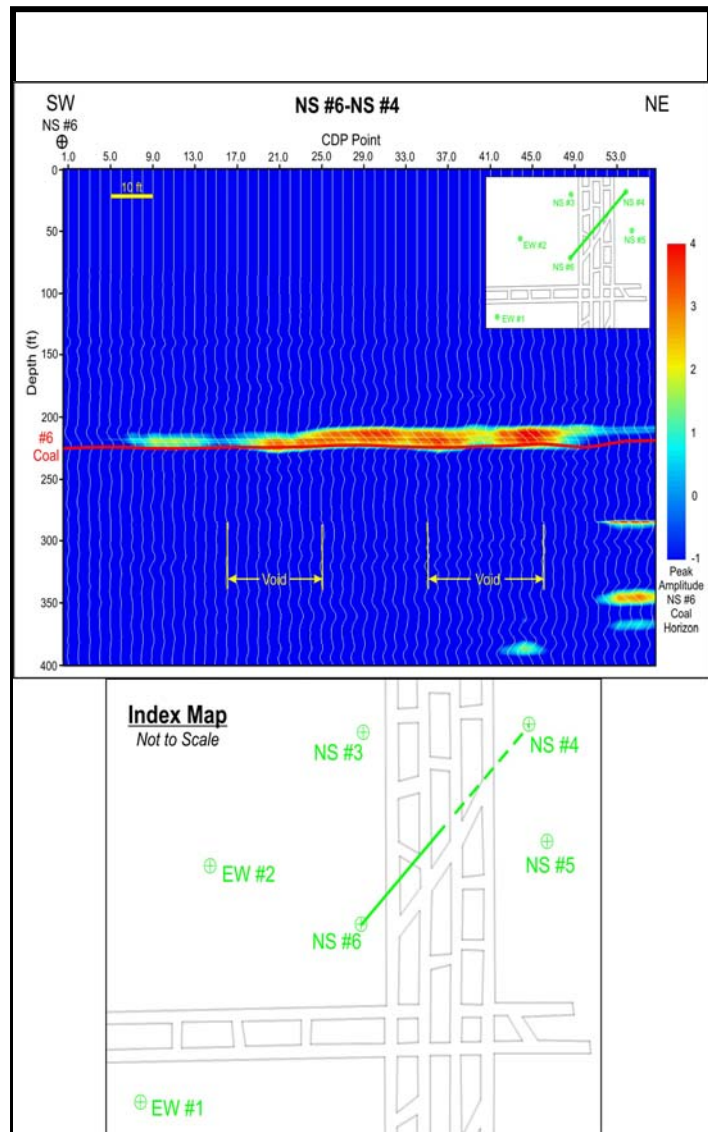


Figure 7. Instantaneous Amplitude from RVSP Profile across the Mains.

color showing the interpreted top of the Herrin #6 along with instantaneous amplitude of the seismic data. The high amplitudes occur primarily near the Herrin #6 coal seam reflector. Peaks in the instantaneous amplitude at the Herrin #6 reflector are observed to correlate with the location of the voids which were determined from a registered historical mine map. It should be noted that the RVSP profile on the figure extends from the source borehole (NS #6) to the end of the data, as shown on the map inset.

In order to visualize the amplitude variation's relationship to the possible mined void locations, the amplitude at the peak of the coal horizon was extracted from each RVSP section. Figure 8 shows the extracted amplitude along the top of the Herrin #6 coal seam at each CDP (common depth point) displayed as color coded dots and overlain on the referenced historical mine map. The color of each point correlates to the relative amplitude along the line, with the "warmer" colors showing high amplitudes and the "cooler" colors showing the lower amplitudes. It is clear that peaks in the amplitude of the reflector correspond to the location of voids due to mining activities.

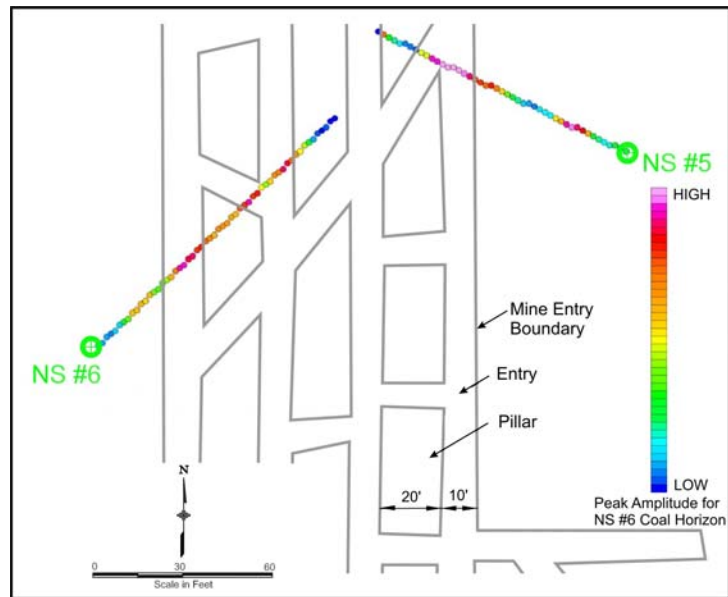


Figure 8 Extracted Instantaneous Amplitude from Herrin #6 Coal Horizon overlain on Historical Mine Map.

Figure 9 shows the extracted amplitudes from Figure 8 displayed in a graph format. On this amplitude graph the locations along the profile where the main entries (obtained from the historical mine map) intersect the profile are shown. The solid line in the index map (Figure 9) represents the area with data coverage. The maxima in the amplitudes along the profile all correspond to the presence of voids. Furthermore, the RVSP amplitudes also show the presence of a pillar corner that approaches the profile location on the historical map. The impact of the pillar corner on the amplitude may be due to errors in the geo-referencing of the historical map. These were observed in the borehole sonar mapping and a more significant portion of the pillar may actually intersect the profile.

Borehole Sonar Mapping – Borehole sonar was used in four confirmation boreholes that intersected voids resulting from old mine workings. The unit used in this survey was a Wet Ferret developed by Carnegie-Mellon University (Figure 10). This unit can be deployed in four

in diameter boreholes. The Wet Ferret consists of a profiling sonar unit, color underwater camera, backlit magnetic compass, support frame, and tether.

The Wet Ferret uses the profiling sonar unit to take measurements up to 300 ft in 360-degree horizontal planes referred to as scans. Scans are referenced using the depth from the ground surface, borehole surface coordinates, and the camera view of the magnetic compass. By taking multiple scans at different elevations, a 360-degree 3-D model of the void can be produced. For this survey, scans were obtained at one ft depth intervals from the top of the void to the point where the instrument encountered obstacles. The scanned void can be geo-referenced and correlated with the magnetic compass and underwater camera integrated into the device. A sample record is shown in Figure 11. The colored dots on the screen represent the strength of the sonar return from a solid surface (walls of coal mine). The unit is clearly able to distinguish the walls of the mine void. The inset image, where the scan was taken at the top of the mine void, shows the presence of a timber roof brace used in the support of the mine roof.

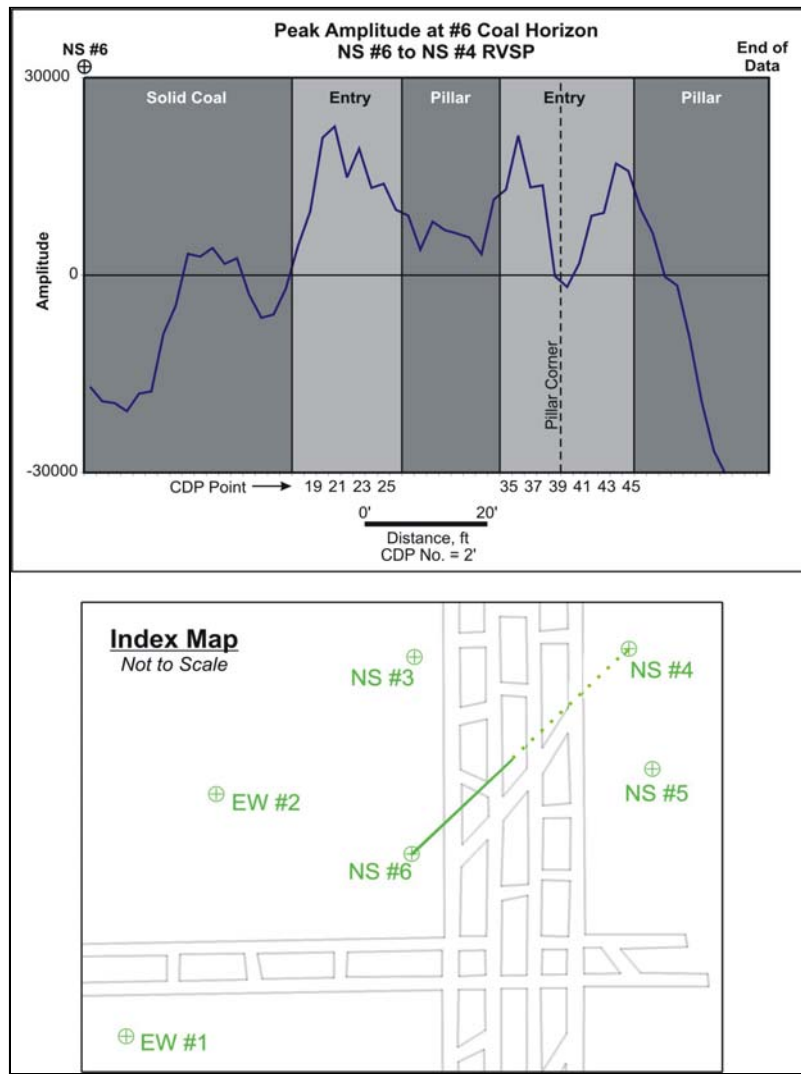


Figure 9. RVSP Peak Amplitude at the Herrin #6 Coal Horizon from NS #6 to NS #4.

The final combined result of the four borehole sonar scans is shown in Figure 12. Each color of the dots represents the interpreted location of the void boundaries from a single borehole sonar survey. The combined result was obtained by positioning the location of the borehole where it intersects the top of the void using borehole deviation data, preliminarily aligning the results using the magnetic compass, then iteratively aligning the results from different boreholes so that the lines of signal returns from the walls of the mine voids align.

The plot clearly shows the north-south oriented mains as well as the diagonal cross-cuts and east-west oriented crossover cut. Based on the results from the borehole sonar, the historical mine map which had been scanned and then positioned using known features was shifted from the actual coordinates by approximately 10 ft to the north and three ft to the west.

CONCLUSIONS AND RECOMMENDATIONS

Several geophysical techniques were employed at the abandoned mine site to evaluate their effectiveness in detecting mine voids. The geophysical demonstrations have shown the RVSP surveys were more effective than the surface P-wave and S-wave reflection surveys at mapping the location of the old mine works at this site. In some cases, the method was able to map individual entries within the mains. The positional error of the RVSP interpretations was approximately three to five ft. This is notably precise considering the depth of the target horizon was 235 ft and that the field geometry was not optimal for RVSP processing. It appeared to provide sufficient accuracy in locating the mine void to allow the placement of confirmation boreholes that reliably intersected the voids. Once the voids were located, a borehole sonar tool was deployed. This allowed mapping of the boundary of water-filled voids to a distance of approximately 100 ft away from the borehole and provided invaluable information that confirmed the historical mine maps as well as allowing the map to be correlated to actual ground location with accuracy of approximately one ft. These two methods provided complementary information that was cost-effective and accurately delineated the vertical and lateral extent of the mine voids.

The RVSP method proved to be practical for detecting mine voids at this site and is anticipated to be effective in other areas with or without good historical information. However, it is recommended that additional tests be performed in other topographic, geologic, and cultural settings to evaluate the effectiveness of the RVSP method in various conditions.



Figure 10. Data Acquisition Using Wet Ferret Tool.

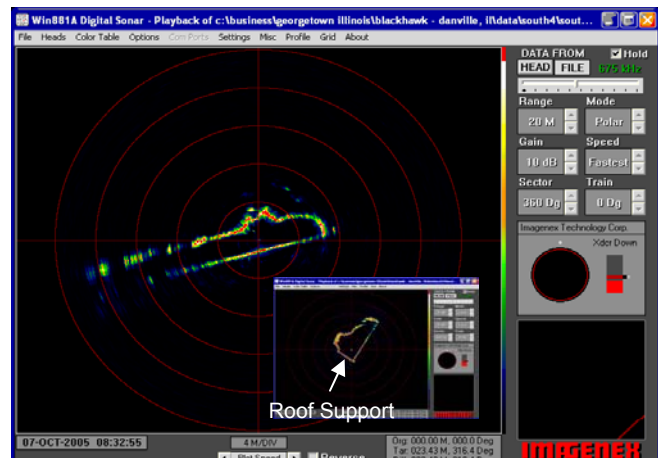


Figure 11. Field Results from Borehole Sonar Tool.

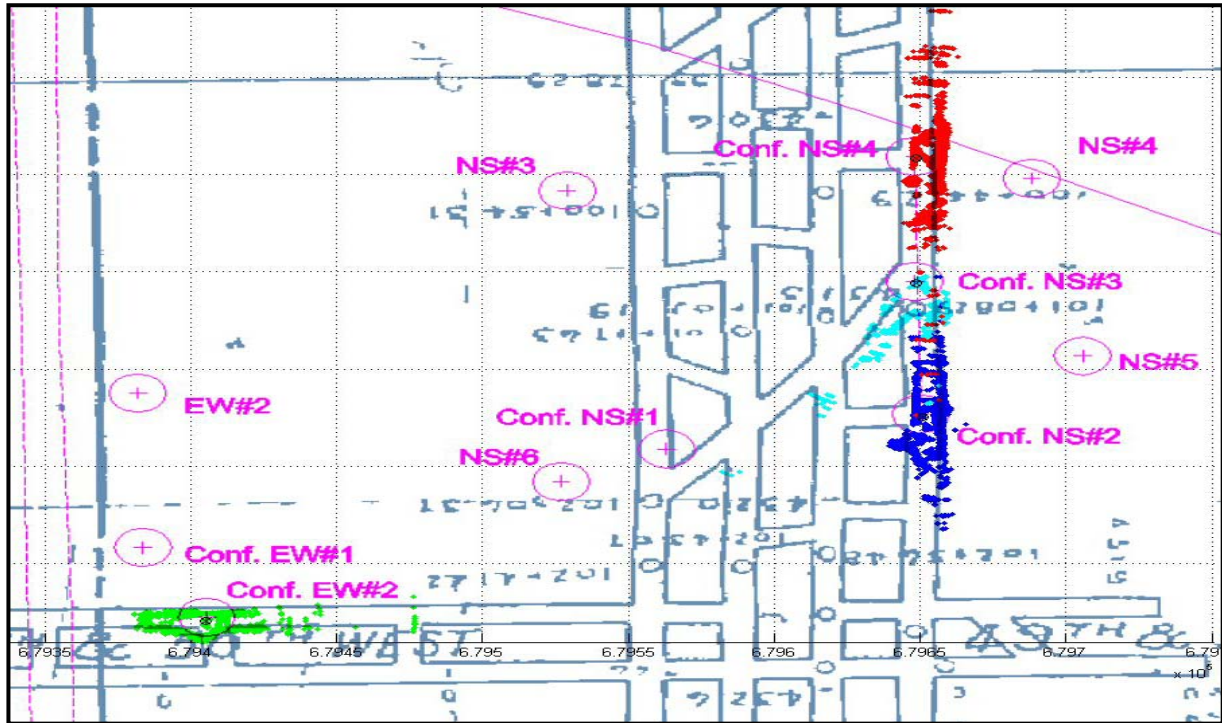


Figure 12. Combined Results of Four Borehole Sonar Survey Overlain on Historical Mine Map.

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References

Paulsson, B., Fuller, B., Karrenbach, M., Huermann, P., Borehole Data: Closer to the Rocks, AAPG Explorer, July 2001, p 22-23.